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in several Scottish English phonemes using ultrasound. QMU
Speech Science Research Centre Working Papers, WP-13.

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Speech Science Research Centre

Quantification of coarticulatory effects in several Scottish English phonemes using ultrasound

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Working Paper WP-13

October 2007



Queen Margaret University

EDINBURGH

Update and Sourcing Information October 2007

This paper is available online in pdf format

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Presentation details:

- This text is based on the oral presentation at Ultrafest IV (a workshop on ultrasound imaging in speech research), 28-29 September 2007, New York University, New York NY, USA.

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Quantification of coarticulatory effects in several Scottish English phonemes using ultrasound

Natalia Zharkova

1. Introduction

In the study reported in this paper, vowel-on-consonant (V-on-C) and consonant-on-vowel (C-on-V) coarticulation was analysed. Results were interpreted and discussed using Coarticulation Resistance (CR) approach.

The CR model of coarticulation originated from research focused on the question how much a sound retains its identity across different phonetic environments (Bladon & Al-Bamerni, 1976). CR has mostly been studied with EPG, EMA and acoustic methods (e.g., Recasens et al. 1997; Fowler & Brancazio 2000; Recasens 2002). An ultrasound study that has addressed CR is reported in Hewlett & Zharkova (under review). In that study, CR of two Southern British English phonemes, /t/ and /a/, was quantified and compared, based on the data from midsagittal tongue contour, and /t/ was shown to be significantly less resistant than /a/. This result contradicted the classification proposed in Recasens et al. (1997), where alveolar consonants had similar CR characteristics to the open unrounded vowel. The contradiction can be explained by the difference in methodologies used in these two works. In Recasens et al. (1997), degree of tongue dorsum activity during production of a sound defined the sound's CR. In Hewlett & Zharkova (under review), CR was defined by the degree of similarity in the whole tongue contour position between productions of a sound in two different contexts. The accent on the tongue dorsum behaviour in the work of Recasens and his associates is partly induced by the articulatory technique used in their study mentioned above (and a number of subsequent studies to date, e.g., Recasens & Espinosa 2007), i.e., EPG. In some other publications (e.g., Recasens 2002), classification of articulatory constraints incorporates data from tongue tip vertical and horizontal displacement, obtained in EMA experiments (see also references cited in Recasens, 2002). Both of these articulatory techniques, however, do not allow for quantifying coarticulatory characteristics of neighbouring sounds based on displacement of the whole midsagittal tongue contour. Such data are particularly valuable when visualising vowels, where typically most of the tongue contour needs to assume a certain position in order to create appropriate resonances.

The aim of this work was to quantify CR values for several Scottish English phonemes, based on whole contour data, and to compare these values to previous quantifications of CR based on other types of data. Midsagittal data were obtained with ultrasound. This technique allows for recording large quantities of data, as it is safe, non-invasive and comparatively easy for participants (Stone, 1999; Stone, 2005).

2. Method

2.1. Data collection

The two subjects were adult female speakers of Standard Scottish English. The data were /C₁V₁#C₁V₁/ sequences from real sentences, with the consonants /p, f, t, s, k, l, r/ and the vowels /a, i/ (where # is a word boundary), in the following sentences:

After that, Pa passed it on to Peter.
His brother P peeped through the hole.
Last month, Mr Fah fasted for two weeks.
Today Mr Phee feels all right.
The head teacher Mrs Tah tasked Teigh to wipe the blackboard.
Peter's buddy Teigh teased Peter.
After that, Mr Sah sat down and started reading.
Promptly, Mr C seized his scissors.
Noticing that, Dr Kah cast an angry look at the boys.
My brother Keigh keeps his secrets.
After dinner, Mr Lah lasted for an hour, and then fell asleep.
His sister Leigh leads the group.
After breakfast, Master Ra raps on the window.
In the morning, Mr Ree reads a newspaper.

The target sequence consisted of the vowel and the consonant separated by the word boundary (underlined in the orthographic version above; henceforth referred to as "VC"). The left context for the target vowel and the right context for the target consonant were chosen to ensure that the target phonemes were minimally affected by any segmental context other than the two surrounding phonemes. Grammatical structure of the sentences was constructed in order to ensure a similar quality of the two vowels surrounding the target consonant. Five tokens of each sentence were collected. The total number of tokens of the VC sequences recorded was therefore 140 (14 sentences x 5 repetitions x 2 subjects).

The participants were given a printout of the sentences for some pre-recording practice. During the recording, the subjects read the sentences as they appeared, one by one, on the computer screen in front of them. The sentences were presented in random order. The subjects were asked to produce the sentences at a comfortable speaking rate.

Synchronised ultrasound and acoustic data were collected using the Queen Margaret University ultrasound system (Zharkova, 2007). The hardware consisted of a Concept M6 Digital Ultrasonic Diagnostic Imaging System and an electronic endocavity transducer type 65EC10EA, with a sector of 120 degrees. The transducer frequency employed in this study was 6.5 MHz. Scanning was performed at a frame rate of 24 frames per second. More technical details on the frame rate can be found in Hewlett & Zharkova (under review); an ultrasound system which will have a much higher frame rate is currently under development (Wrench, 2007). A helmet, with the transducer attached, was used for immobilising the head in relation to the ultrasound transducer (Vazquez Alvarez & Hewlett, 2007). The software used for data recording and analysis was the programme "Articulate Assistant Advanced" Version 2.05, developed by Articulate Instruments. The acoustic signal was recorded using an Audiotecnica ATM10a microphone. All the recordings were made in a sound-treated studio. The ultrasound scanner and the computer running the software were located in an adjacent room, to reduce background noise on the acoustic recording.

2.2. Analysis

2.2.1. Frame selection and spline fitting

Two frames were selected from each VC sequence, one from the middle of the vowel and one from the middle of the consonant (for the stops, the frame was selected at the middle of the closure). For each frame, a cubic spline was manually fitted to the tongue surface contour, as follows. A gridline consisting of 42 lines was superimposed on the ultrasound screen. The researcher defined each spline interactively on the screen, by specifying positions of the knots located at the intersection of the gridlines and the tongue contour. Fig. 1 shows the ultrasound frame corresponding to the middle of /s/ in a token of /is/, with the grid superimposed on the tongue contour (on the left), and with the spline fitted to the tongue surface contour (on the right).

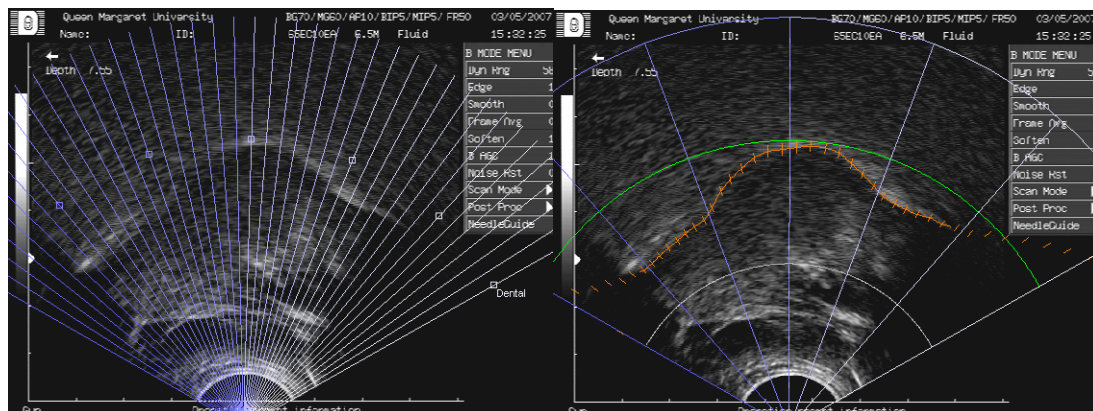


Fig. 1. Ultrasound frame at the middle of /s/ in a token of /is/, produced by the subject S1. On the left: the grid is superimposed on the tongue contour. On the right: the cubic spline (orange) is fitted to the tongue surface contour. The ruler on the ultrasound screen is in cm. The tongue tip is on the right.

Within the Articulate Assistant Advanced software, each spline was defined in terms of xy values, for storage in a text file. The mean number of xy values per spline was 85, ranging from 66 to 104. The Euclidean distance between pairs of adjacent data points ranged from 0.5 mm to 6.1 mm, with the mean of 1 mm.

2.2.2. Comparison of curve sets

Each text file was imported into Matlab for plotting and analysis. All the curves in a set were reduced to the same number of points. The curve having the smallest number of points was selected, and all the remaining curves were reduced, starting with the point having the smallest x value (corresponding to the posterior end of the tongue).

Tongue curve comparison was carried out using the technique introduced in Hewlett & Zharkova (under review), which involves calculating mean nearest neighbour distances between curves. A detailed description of the technique can be found in Hewlett & Zharkova (under review). Henceforth, the word “distance” will be used to signify the mean nearest neighbour distance between a pair of curves.

The presence of a V-on-C effect or a C-on-V effect was signified by a significant difference between across-environment distance and within-environment distances, calculated as follows. Across-environment distance (for example, the distance between /s/ in /as/ and /s/ in /is/) was calculated by taking each one of the curves for the phoneme in one environment and measuring its distance from each of the curves,

in turn, of that phoneme in the other environment (25 distances in all). Within-environment distance (for example, the distance between each one of the five curves of /s/ in /as/ and each of the other four curves) was calculated by taking each one of the curves for the phoneme in one environment and measuring its distance from each of the curves, in turn, of the other tokens of the phoneme in that same environment (ten distances in all). For ascertaining the significance level of a difference between across-environment distance and within-environment distance, the set of across-environment distances (25 values) was compared with each set of within-environment distances (10 values). One-way Univariate ANOVAs were conducted in SPSS, separately for each subject. The Tukey HSD Post Hoc test was applied when the assumption of equal variances of the dependent variable was not violated. The Games-Howell Post Hoc test was applied when the assumption of equal variances of the dependent variable was violated. For a difference to be deemed significant, a probability of less than 0.05 was required in the Post Hoc test between the across-environment distances and each of the within-environment distances; and absence of a significant difference was required between the two within-environment distances.

Comparison of the curves for the consonant in the context of two vowels provided a measure of V-on-C effect. Comparison of the curves for the vowel in the context of each pair of consonants provided a measure of C-on-V effect. All calculations were carried out separately for each subject. Seven different consonants in the context of two vowels were analysed to check for the presence of the V-on-C effect. Each of the two vowels in the context of each of the 21 pairs of consonants was analysed to check for the presence of the C-on-V effect.

The across-environment distance for a consonant in the context of two vowels was deemed to represent the size of the V-on-C effect, and the across-environment distance for a vowel in the context of a pair of consonants was deemed to represent the size of the C-on-V effect. In the event of a presence of effect, individual consonants were compared to each other according to the size of the V-on-C effect, and vowels in the context of different pairs of consonants were compared to each other according to the size of the C-on-V effect. This was achieved by means of a Univariate ANOVA with a Games-Howell Post-Hoc test, separately for each subject. The V-on-C effect was compared with the C-on-V effect, separately for each subject, by means of a Univariate ANOVA including pairwise comparisons with Bonferroni adjustment.

2.2.3. *Measurement of coarticulation resistance*

Coarticulation resistance was measured for the consonants and the vowels, using the formula:

$$CR_R = \frac{(P - R_P) + (Q - R_Q)}{P - Q}$$

In the formula, R is the phoneme being measured for CR, P and Q are the phonemes providing the alternative conditioning environments, R_P is R in the environment of P and R_Q is R in the environment of Q. The numerator quantifies the distance between the phoneme being measured for CR and its two conditioning environments. The denominator is the distance between the two conditioning environments. Therefore, this measure of CR quantifies how much the tongue contour of the phoneme in question deviates from the two conditioning environments. Theoretically, a phoneme would have a zero CR if its tongue contour was absolutely identical to the tongue

contours of both adjacent sounds. The other end of the CR scale is partly defined by how close to each other are the contours of the two context sounds. In the case of conditioning sounds having a very similar place and manner of articulation (e.g., /s/ and /z/), the distance in the denominator of the formula would be very small. However, due to variability in articulations across repetitions, in reality the tongue contour of the two conditioning sounds would never be zero; hence, the resistance of a speech sound could never be infinite.

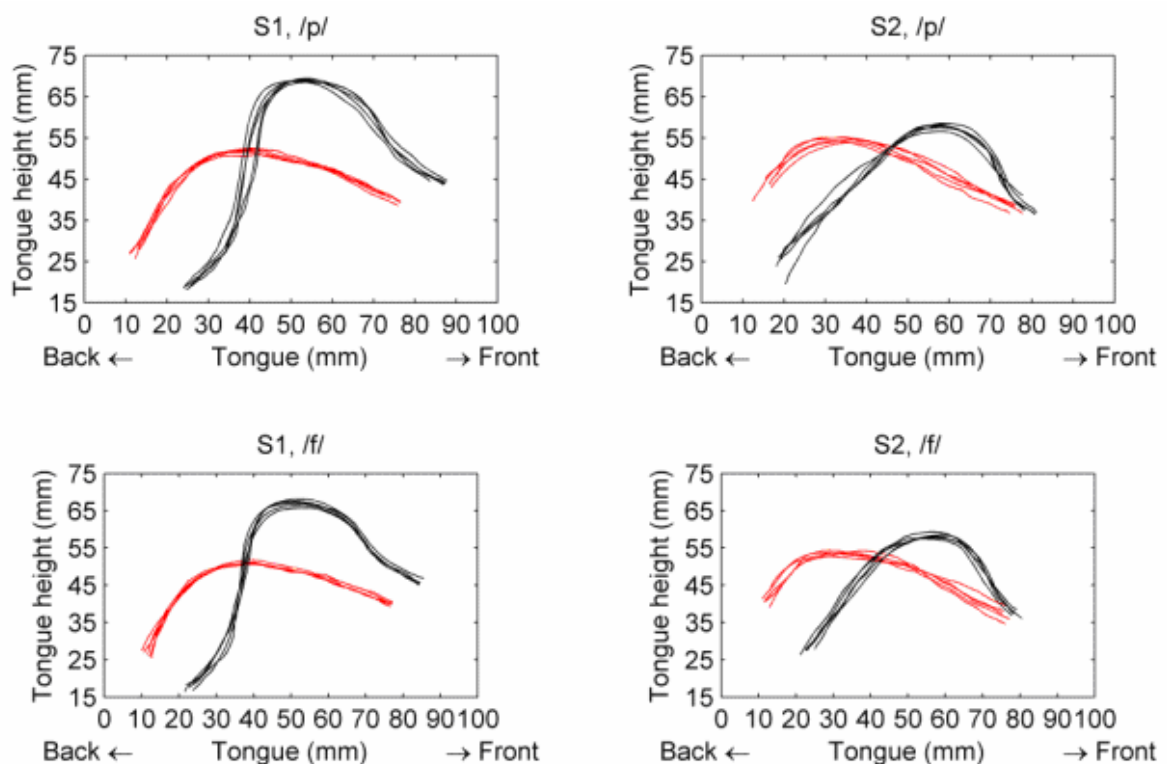
This formula was applied separately for each subject. CR was calculated for each consonant in two vowel environments. CR values of individual consonants were compared by a Univariate ANOVA with a Games-Howell Post-Hoc test, separately for each subject. For each vowel, CR was measured separately in each of the 21 pairs of consonant environments. Vowels in the context of different pairs of consonants were compared to each other according to their CR value, by a Univariate ANOVA with a Games-Howell Post-Hoc test, separately for each subject. CR values for consonants and vowels were compared using a Univariate ANOVA including pairwise comparisons with Bonferroni adjustment.

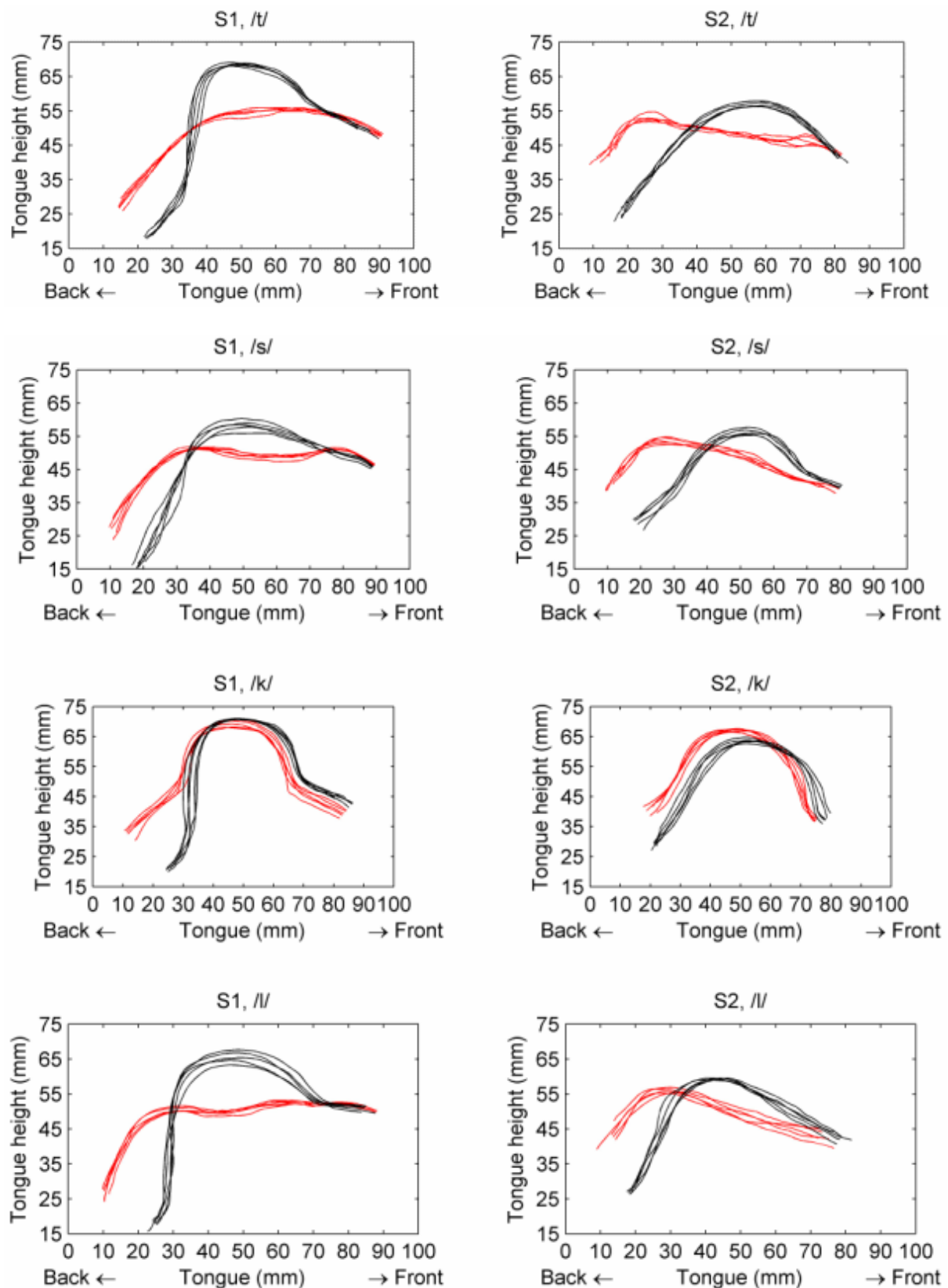
3. Results

3.1. Consonants

3.1.1. V-on-C effect

Fig. 2 shows tongue contour outlines for each of the seven consonants in two contrasting vocalic contexts, separately for each subject.





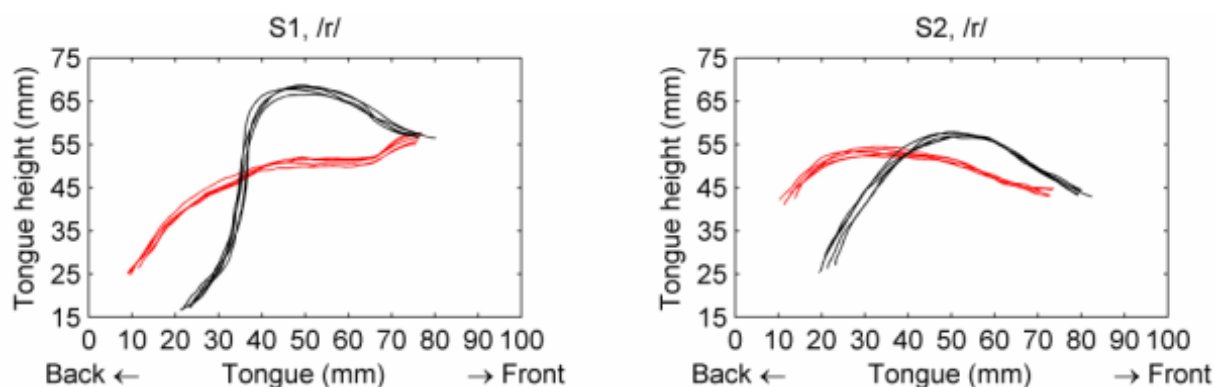


Fig. 2. Tongue contour outlines for the consonants in two contrasting vocalic contexts, separately for each subject. Red lines – consonant curve in the context of /a/, black lines – consonant curve in the context of /i/.

In Table I, there are mean across-environment distances for all consonants (i.e., sizes of the V-on-C effect). For each consonant, for each subject separately, ANOVA results showed that there was a significant V-on-C effect (statistical figures are also presented in Table I). For S1, Games-Howell Post-Hoc tests showed that for each consonant the across-environment distance was significantly greater than both within-environment distances, at the 0.001 level, while there was no significant difference between two within-context distances. There were similar results for S2, produced by Tukey HSD Post-Hoc tests for /l/ and /r/, and by Games-Howell Post-Hoc tests for all other consonants.

Consonant	S1		S2	
	Effect size	<i>F</i>	Effect size	<i>F</i>
/p/	13.38	5304.61	9.29	905.50
/f/	12.64	5187.34	8.98	1787.00
/t/	7.61	1433.47	7.75	2679.26
/s/	6.74	353.66	7.40	1229.10
/k/	6.19	203.03	4.68	183.13
/l/	9.27	1024.08	6.96	335.67
/r/	10.93	3025.01	7.50	1699.55

Table I. Mean across-environment distances (i.e., V-on-C effect sizes) for consonants in two subjects, in mm. *F* values from ANOVA results are also presented ($df = 2$ and $p < 0.001$ in all cases).

ANOVA demonstrated a significant difference in effect size among consonants for both subjects, at the 0.001 level (S1: $F = 423.61$, $df = 6$; S2: $F = 148.79$, $df = 6$). The Post-Hoc test for S1 showed that all consonants were significantly different from each other in V-on-C effect size (at the 0.001 level), except the pairs /s/ – /t/ and /s/ – /k/. For S2, the Post-Hoc test showed no significant differences in the pairs /p/ – /f/, /t/ – /r/ and /t/ – /s/; the consonants /s/, /l/ and /r/ did not significantly differ from each other; there were significant differences between all other pairs of consonants, at the 0.001 level (except 0.01 level for the pair /t/ – /l/).

3.1.2. Measuring CR in consonants

Table II contains CR values for each consonant in the two vowel environments, as well as all the constituents of the CR formula.

	S1				S2			
Consonant	/a/-C	/i/-C	/a/-/i/	CR	/a/-C	/i/-C	/a/-/i/	CR
/p/	0.72	1.00	14.01	0.12	1.23	2.78	11.33	0.35
/f/	0.86	1.81	14.03	0.19	1.46	2.90	12.19	0.36
/t/	5.62	2.09	12.92	0.60	3.34	3.75	12.00	0.59
/s/	2.68	5.77	13.05	0.65	1.40	4.61	11.44	0.53
/k/	5.37	2.30	11.50	0.67	6.91	3.79	11.68	0.92
/l/	3.60	2.95	13.09	0.50	1.54	4.61	10.49	0.59
/r/	2.97	1.36	13.19	0.33	2.09	3.58	11.60	0.49

Table II. CR values for consonants in two subjects (in bold). The table also contains the values included in the formula for calculating CR: /a/-C – the distance between the vowel /a/ and the consonant in its context; /i/-C – the distance between the vowel /i/ and the consonant in its context; /a/-/i/ – the distance between the two conditioning vowels.

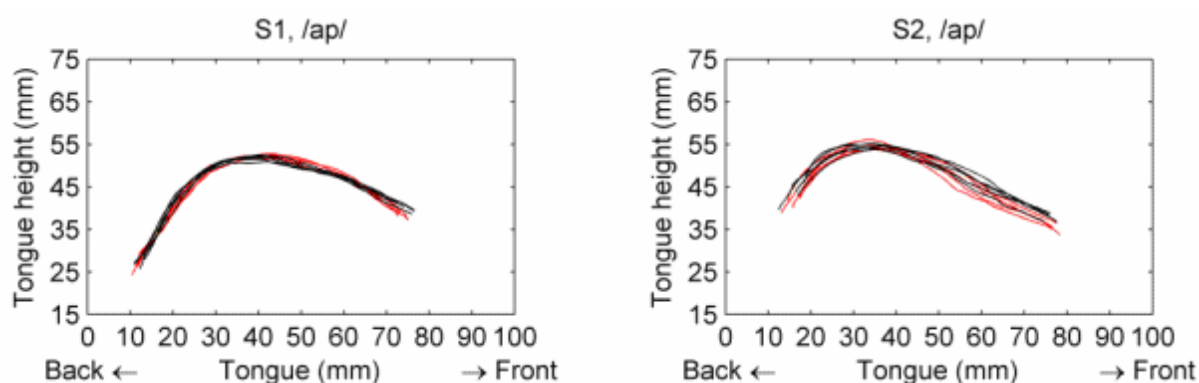
The table shows that the CR values in consonants range from 0.12 to 0.92. The average CR value for consonants is 0.44 in S1, and 0.55 in S2. The consonants are ranged, according to their CR value (in increasing order), as follows: in S1, /p, f, r, l, t, s, k/; in S2, /p, f, r, s, l, t, k/. The average CR value for the consonants, across subjects, is 0.49.

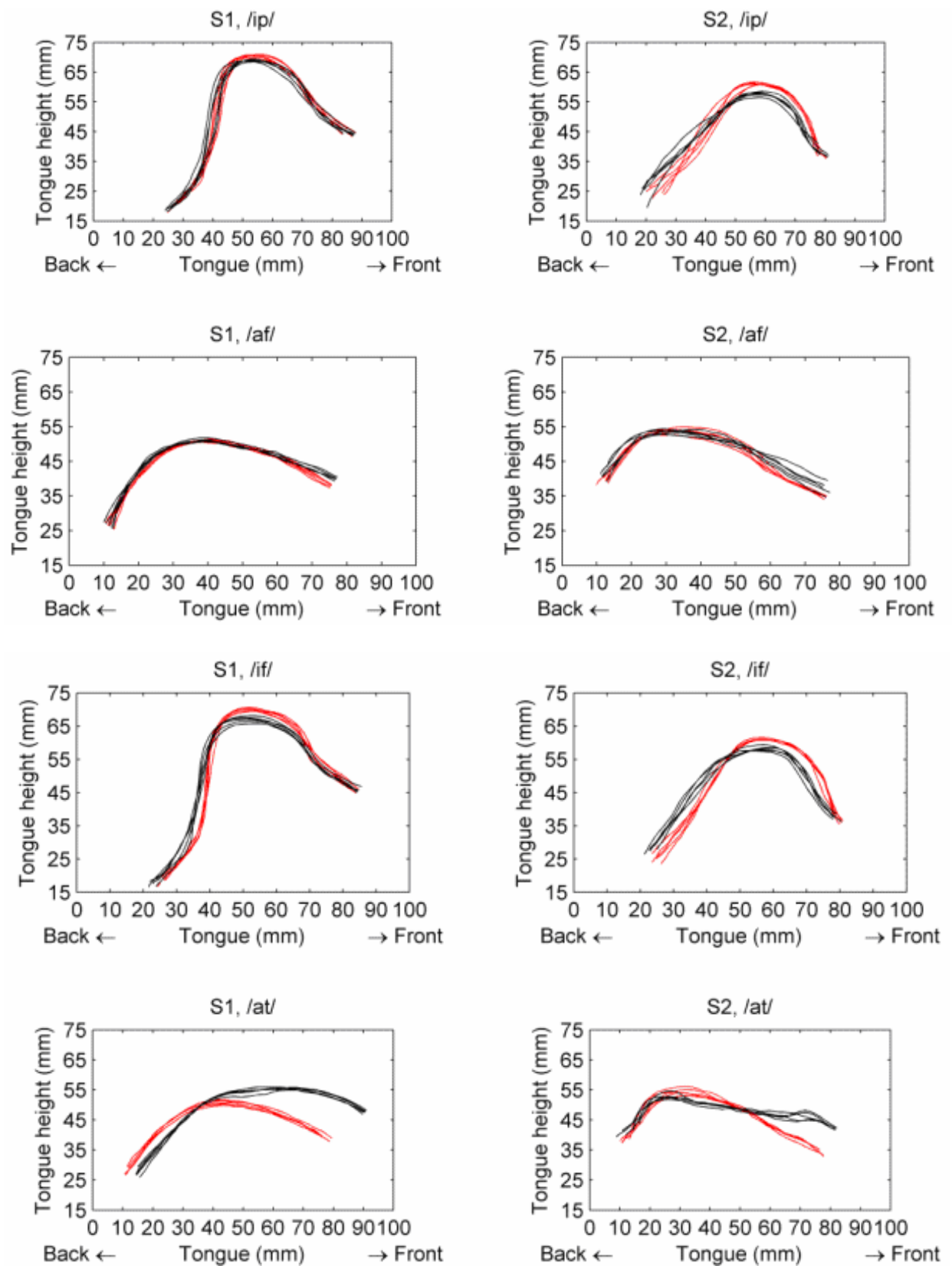
ANOVA results show that there is a significant difference in CR among the consonants, at the 0.001 level, for both subjects. The Games-Howell Post-Hoc test conducted for S1 demonstrates that all consonants are significantly different from each other, except the pair /s/-/k/ and the pair /s/-/t/. The Games-Howell Post-Hoc test conducted for S2 shows that all consonants differ significantly from each other, except the pairs /p/-/f/, /s/-/r/, /s/-/l/ and /t/-/l/.

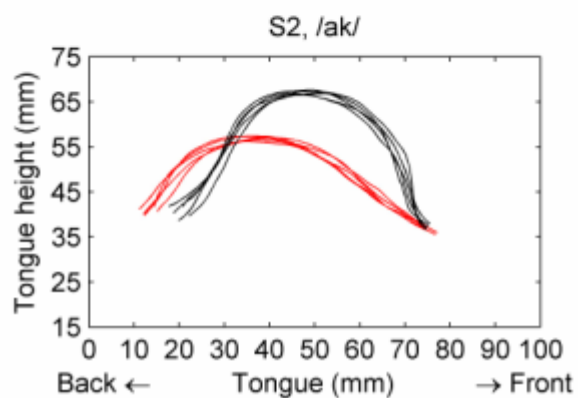
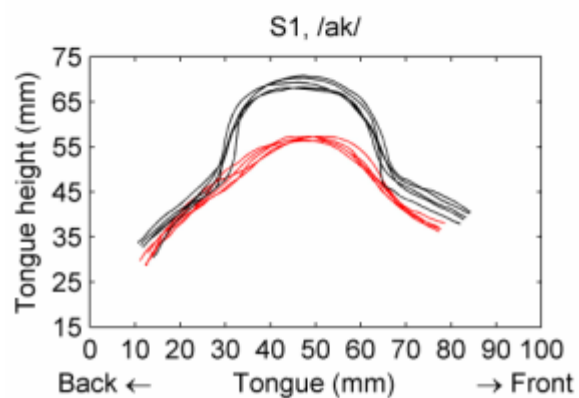
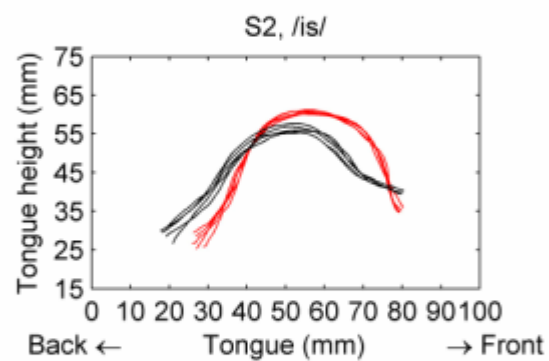
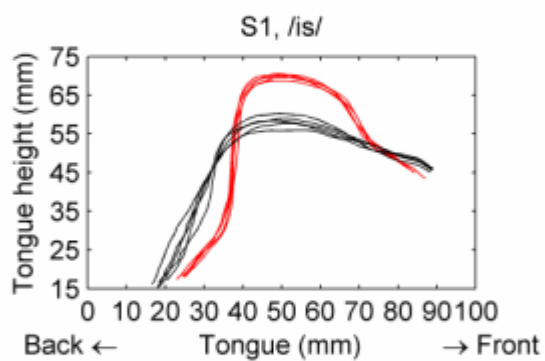
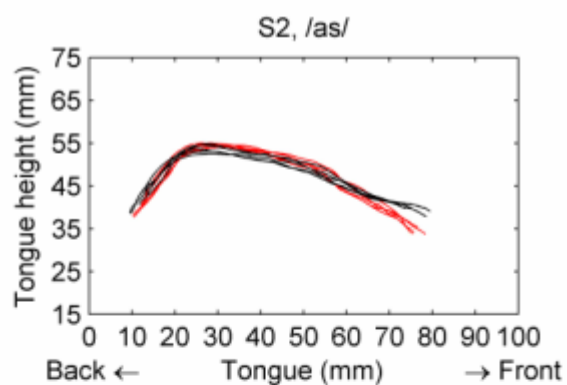
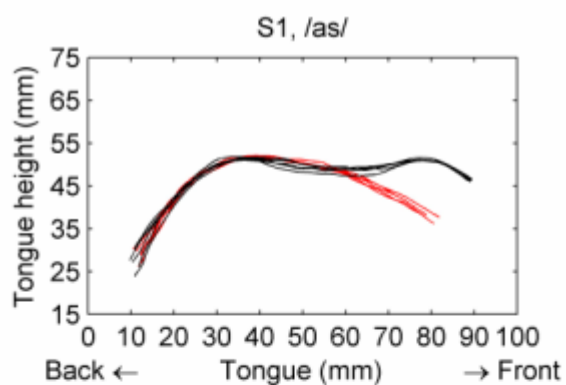
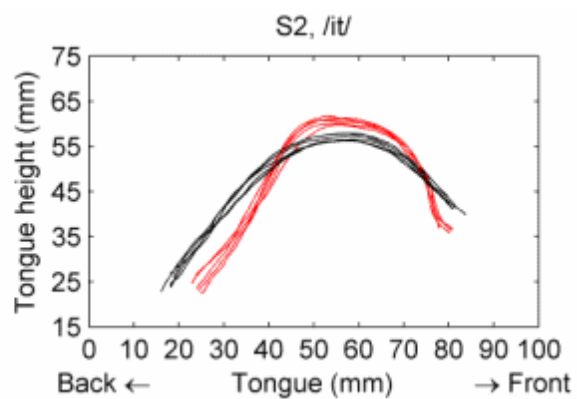
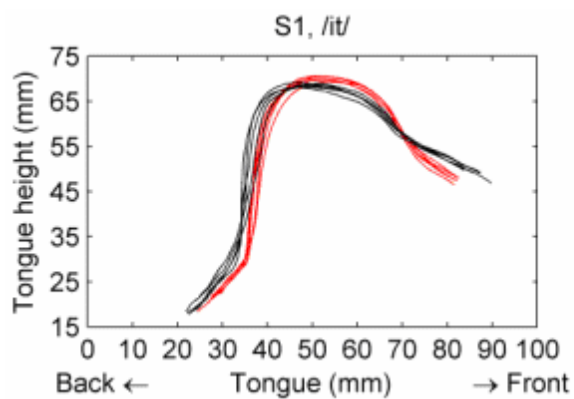
3.2. Vowels

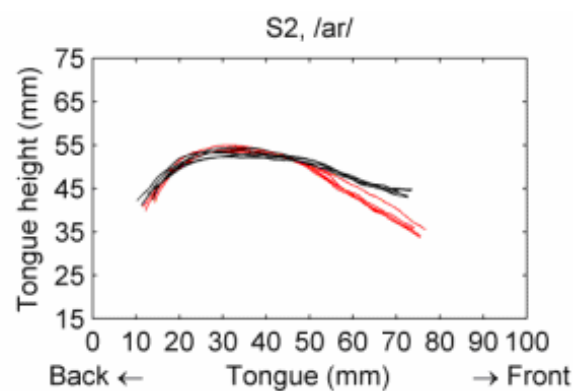
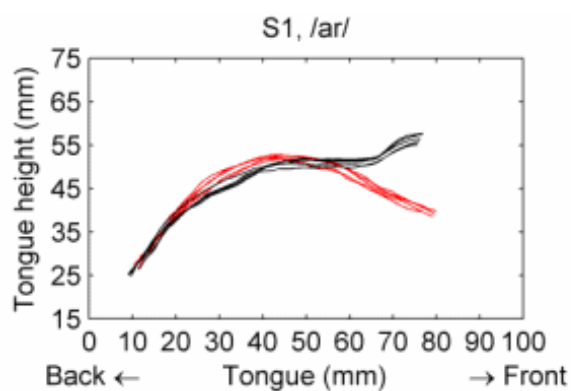
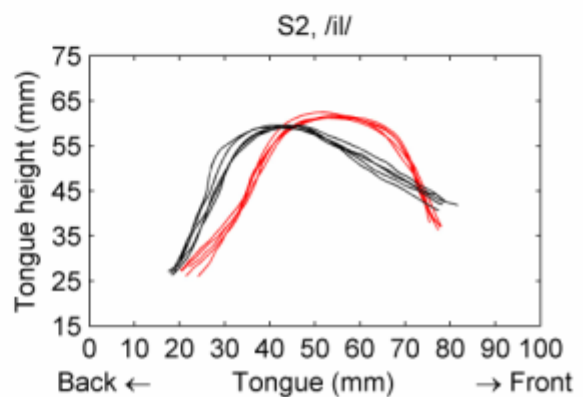
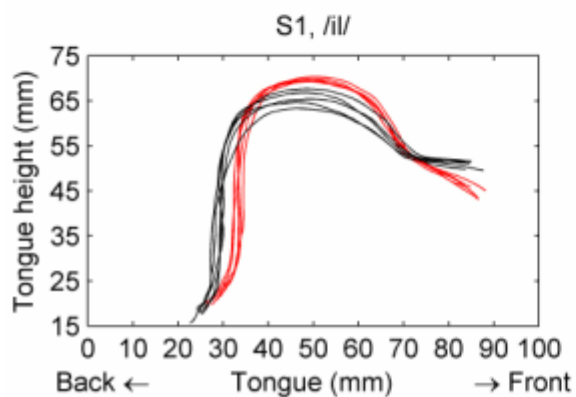
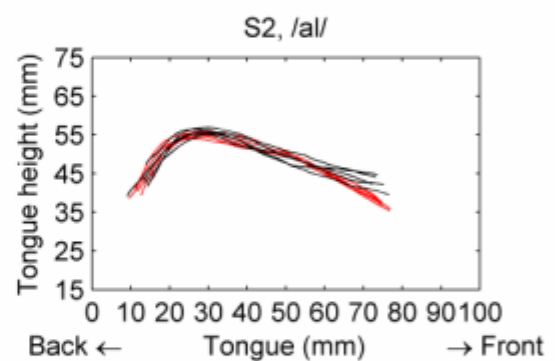
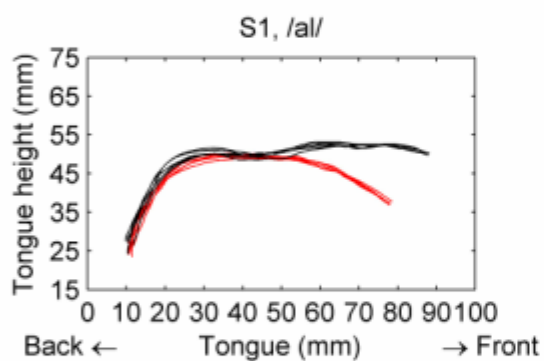
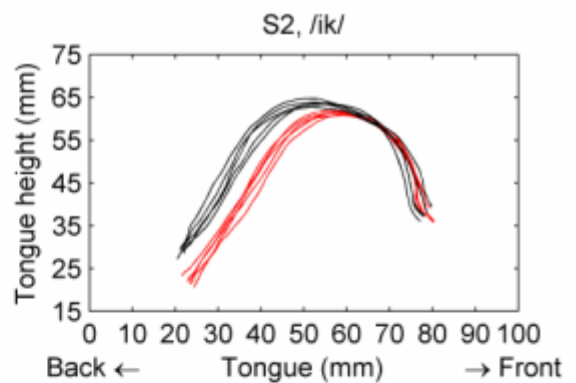
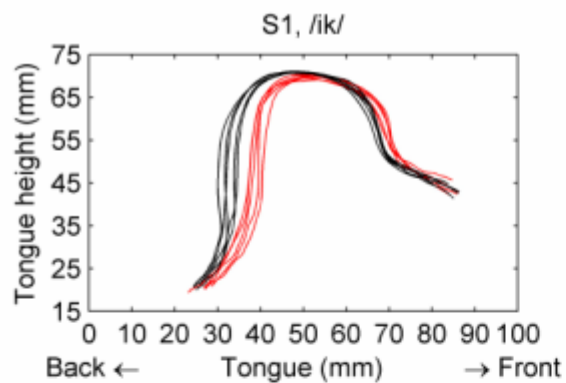
3.2.1. C-on-V effect

Fig. 3 shows tongue contour outlines for the vowel and the adjacent consonant, for all 14 different VC types, separately for each subject. For the reasons of space, it is not possible to reproduce 42 graphs with two vowel curves in the context of each consonant pair.









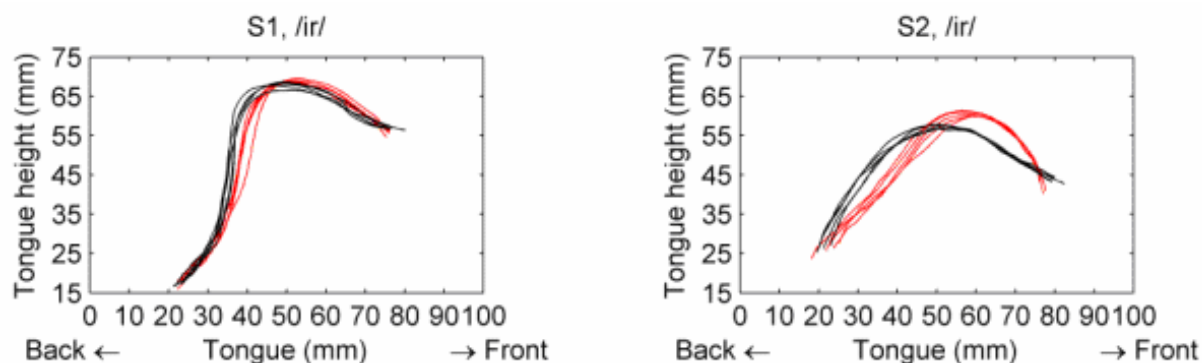


Fig. 3. Tongue contour outlines for the vowel and the adjacent consonant, for 14 VC types, separately for each subject. Red lines – the vowel, black lines – the consonant.

In Table III, there are mean across-environment distances for the two vowels in all pairs of consonant contexts (i.e., sizes of the C-on-V effect). ANOVA results are also presented in this table.

	In the context of /a/						In the context of /i/					
	S1			S2			S1			S2		
	Size	F	α	Size	F	α	Size	F	α	Size	F	α
/p – f/	0.94	13.21	0.01	N/E			N/E			N/E		
/p – t/	1.32	29.60	0.001	N/E			1.27	20.36	0.001	N/E		
/f – t/	1.23	25.43	0.001	N/E			N/E			N/E		
/p – s/	1.10	28.33	0.001	N/E			1.56	37.71	0.001	N/E		
/f – s/	1.24	27.36	0.001	1.20	5.99	0.05	1.09	11.47	0.001	1.11	8.74	0.01
/t – s/	1.16	16.13	0.01	N/E			1.00	4.23	0.05	N/E		
/p – k/	2.23	218.41	0.001	2.25	43.46	0.001	1.70	18.52	0.05	N/E		
/f – k/	2.56	323.86	0.001	2.53	65.40	0.001	N/E			N/E		
/t – k/	2.42	201.47	0.001	2.47	74.63	0.001	N/E			N/E		
/s – k/	2.52	374.95	0.001	1.95	34.18	0.001	N/E			1.28	13.94	0.05
/p – l/	1.57	125.34	0.001	1.73	14.66	0.05	2.61	164.43	0.001	2.50	49.04	0.001
/f – l/	1.20	46.06	0.001	1.86	71.22	0.001	2.05	97.28	0.001	2.56	119.33	0.001
/t – l/	1.36	42.71	0.001	1.55	17.94	0.001	1.90	59.16	0.001	2.26	59.41	0.001
/s – l/	1.20	40.18	0.001	N/E			1.46	40.57	0.001	2.18	93.62	0.001
/k – l/	3.06	487.04	0.001	1.98	37.37	0.001	1.93	29.76	0.001	2.46	55.81	0.001
/p – r/	1.20	10.46	0.05	N/E			2.29	60.17	0.001	N/E		
/f – r/	1.45	18.31	0.001	N/E			1.92	100.03	0.001	1.75	16.10	0.01
/t – r/	N/E			N/E			1.88	128.54	0.001	1.80	13.81	0.01
/s – r/	1.15	11.94	0.05	N/E			1.80	92.22	0.001	1.98	31.17	0.001
/k – r/	2.07	138.14	0.001	2.27	53.93	0.001	2.41	81.78	0.001	1.85	14.81	0.01
/l – r/	1.73	52.47	0.001	1.40	17.35	0.001	3.04	350.09	0.001	2.12	41.48	0.001

Table III. Mean across-environment distances (i.e., C-on-V effect sizes) for vowels in two subjects, in mm, separately for each pair of consonant contexts (column “Size”). *F* values from ANOVA results are also presented. The *df* value equals 2 in each case. “ α ” signifies “significance level”. “N/E” signifies “no effect”.

Table III shows that in some consonant environments, especially those including labial consonants, the C-on-V effect was significant only on the 0.01 or 0.05 level, and sometimes not present at all. There was a significant C-on-V effect for the vowel /a/ in the subject S1, in all pairs of consonant environments, except /t – r/. In S2, consonant

pairs involving labial phonemes tended to have no significant effect on /a/; also, the pair /t – s/ produced no significant effect on /a/. All consonant pairs including /k/ had a significant effect on /a/ in S2. Except for the pair /l – s/, all consonant pairs including /l/ also had a significant effect on /a/ in S2. For the vowel /i/ in S1, the pairs /p – f/ and /f – t/ did not have a significant effect on the vowel. Also, three consonant pairs involving /k/ (/f – k/, /t – k/, /s – k/) did not significantly affect the vowel /i/. In S2, most consonant pairs including /p/ did not significantly affect /i/. Every consonant pair including /l/ significantly affected the vowel /i/. There was no significant effect on the vowel from the pairs /f – t/, /t – s/, /f – k/ and /t – k/.

For /a/ in S1, ANOVA demonstrated a significant difference in effect size between pairs of consonants, at the 0.001 level (S1: $F = 108.53$, $df = 19$). Table III shows that the greatest effect sizes on the vowel /a/ in S1 were in the case of consonant pairs including the consonant /k/. The Post-Hoc test for S1 showed that effect sizes of all consonant pairs including the consonant /k/ were significantly different from effect sizes of all other consonant pairs, at the 0.001 level (except the pairs /k/ – /r/ and /l/ – /r/, which were different from each other on the 0.01 level). Consonant pairs including labials, as well as pairs of alveolar consonants tended to group together and to exhibit no significant differences in effect sizes. For /i/ in S1, ANOVA demonstrated a significant difference in effect size between pairs of consonants, at the 0.001 level (S1: $F = 56.64$, $df = 15$). Consonant pairs including /l/ and /r/ had a greater effect on the vowel /i/ than other consonant pairs; the pair /l/ – /r/ had a significantly greater effect on /i/ than every other pair of consonants, except /p/ – /l/. For /a/ in S2, ANOVA demonstrated a significant difference in effect size between pairs of consonants, at the 0.001 level (S1: $F = 23.84$, $df = 10$). Table III shows that in S2, as well as in S1, consonant pairs including the consonant /k/ had the greatest effect on /a/. The Post-Hoc test for S2 showed that the consonant pairs with a higher effect tended to significantly differ from the consonants with a lower effect. For /i/ in S2, ANOVA demonstrated a significant difference in effect size between pairs of consonants, at the 0.001 level (S1: $F = 24.39$, $df = 11$). Consonant pairs including /l/ had a greater effect on the vowel /i/ than other consonant pairs; consonant pairs including /r/ followed them in effect size. All consonant pairs including /l/ were significantly different from the two consonant pairs with the smallest effect size, i.e., /f/ – /s/ and /s/ – /k/.

C-on-V effect sizes for /a/ and /i/ were compared using a Univariate ANOVA, separately for each subject. In both subjects, the vowel /i/ was affected more than /a/. In S1, the average size of the C-on-/a/ effect was 1.64 mm, and the average size of the C-on-/i/ effect was 1.87 mm. In S2, the average size of the C-on-/a/ effect was 1.93 mm, and the average size of the C-on-/i/ effect was 1.99 mm. In S1, the difference between /a/ and /i/ was significant ($F = 28.60$, $df = 1$, $p < 0.001$); in S2, the difference was not significant.

3.2.2. Measuring CR in vowels

Table IV contains CR values for each vowel in 21 different pairs of consonant contexts, as well as the denominator for the CR formula, i.e., the distance between the conditioning consonants. Distances between the vowel and each of the pair of consonants can be found in columns 2-3 and 6-7 of Table II, for S1 and S2, respectively.

/a/						/i/					
S1			S2			S1			S2		
C	C1-C2	CR	C	C1-C2	CR	C	C1-C2	CR	C	C1-C2	CR
pk	6.54	0.93	sk	8.68	0.96	pr	2.79	0.91	pl	4.62	1.66
fk	6.49	0.96	kl	8.61	0.99	pl	4.18	0.97	pk	3.99	1.69
ft	6.40	1.01	fk	8.29	1.01	pk	3.27	1.08	fl	4.37	1.76
fr	3.76	1.02	pk	7.86	1.04	kr	3.30	1.13	fk	3.63	1.94
pr	3.59	1.03	kr	8.27	1.09	ps	5.90	1.15	sk	4.35	1.98
pt	6.17	1.03	tk	8.84	1.16	sr	5.95	1.20	kl	4.21	2.03
kr	7.89	1.06	pl	1.97	1.48	lr	3.21	1.37	kr	3.44	2.16
pl	4.08	1.06	pt	2.89	1.60	sk	5.61	1.44	tk	3.39	2.27
sk	6.83	1.18	fl	1.89	1.72	pt	2.26	1.47	tl	3.72	2.30
fl	3.76	1.19	pr	1.88	1.82	fk	2.73	1.54	pr	2.82	2.45
kl	7.26	1.24	ps	1.53	1.84	ts	5.10	1.56	fr	2.46	2.78
ps	2.72	1.26	sl	1.68	1.90	fl	2.96	1.62	sl	3.12	3.02
fs	2.55	1.40	ft	2.54	2.02	kl	3.27	1.63	fs	2.22	3.07
tk	7.89	1.40	pf	1.33	2.13	fs	4.72	1.64	ps	2.58	3.07
sr	3.13	1.84	sr	1.72	2.13	tk	2.72	1.64	ft	2.17	3.13
ts	4.06	2.08	ts	2.08	2.31	fr	1.87	1.72	lr	2.71	3.20
pf	0.79	2.14	tl	2.20	2.32	tl	2.82	1.85	pt	2.07	3.57
lr	3.00	2.21	fr	1.70	2.46	pf	1.61	1.98	ts	2.37	3.58
tl	3.90	2.39	lr	1.64	2.61	sl	4.07	2.25	sr	2.17	3.93
tr	3.21	2.71	fs	1.20	2.66	tr	1.43	2.46	pf	1.44	4.24
sl	1.92	3.33	tr	1.86	2.96	ft	1.58	2.50	tr	1.57	4.77

Table IV. CR values for vowels in two subjects. Each of the four sets of values (S1 /a/, S2 /a/, S1 /i/ and S2 /i/) is arranged in increasing order. Homorganic consonant pairs are highlighted. The table also contains the values of the denominator for the CR formula, i.e., distances between the conditioning consonants ("C1-C2").

The table shows that the CR values in vowels range from 0.91 to 4.77. The average CR value for vowels is 1.56 in S1, and 2.30 in S2. It can be seen from the table that higher CR values in vowels are observed in the context of homorganic consonants. The average CR value for the vowels, across subjects, is 1.93. CR values of the vowels in the context of different pairs of consonants were compared to each other, and in both subjects there were significant differences, at the 0.001 level, with $df = 20$ (/a/ in S1: $F = 178.23$; /a/ in S2: $F = 21.36$; /i/ in S1: $F = 33.62$; /i/ in S2: $F = 31.44$).

CR values of /a/ and /i/ were compared using a Univariate ANOVA, separately for each subject. In both subjects, the vowel /i/ exhibited higher CR values than /a/. In S1, the mean CR value of /a/ was 1.55 mm, and the mean CR value of /i/ was 1.58 mm. In S2, the mean CR value of /a/ was 1.82 mm, and the mean CR value of /i/ was 2.79 mm. In S1, the difference between /a/ and /i/ was not significant; in S2, this difference was significant ($F = 232.17$, $df = 1$, $p < 0.001$).

3.3. Comparing consonants and vowels

In S1, the average size of the V-on-C effect was 9.54 mm, and the average size of the C-on-V effect was 1.74 mm. In S2, the average size of the V-on-C effect was 7.51 mm, and the average size of the C-on-V effect was 1.96 mm. The two effects were compared, and the difference was highly significant (S1: $F = 5606.75$, $df = 1$, $p < 0.001$; S2: $F = 4927.02$, $df = 1$, $p < 0.001$). Pairwise comparisons with Bonferroni

adjustments showed that in both subjects the V-on-C effect was significantly greater than the C-on-V effect, at the 0.001 level.

Comparison of CR values in consonants and vowels produced significant differences (S1: $F = 520.57$, $df = 1$, $p < 0.001$; S2: $F = 414.43$, $df = 1$, $p < 0.001$). Pairwise comparisons with Bonferroni adjustments showed that in both subjects the CR value for vowels was significantly greater than the CR value for consonants, at the 0.001 level.

4. Discussion

4.1. Consonants

Comparison of different consonants according to their CR values and to the size of the V-on-C effect showed that labial consonants were significantly less resistant to vocalic influence than lingual consonants. These findings are consistent with previous research, where lingual consonants have been found to resist to lingual coarticulation more than non-lingual consonants (e.g., EPG evidence in Recasens, 1999; EMA evidence in Fowler & Brancazio, 2000; ultrasound evidence in Zharkova, 2007).

In both subjects, /k/ experienced the smallest V-on-C effect, and it had the greatest CR value among all consonants. This result is in accordance with EPG and acoustic results presented in Recasens et al. (1997). In that study, Catalan consonant /k/, along with /p/ and /f/, was assigned the highest possible value for resistance to vocalic coarticulation. Recasens and colleagues studied anticipatory and carryover V-on-C and V-on-V effects in sequence pairs like /iCi/ - /iCa/ and /iCi/ - /aCi/. Their CR classification of velar and alveolopalatal consonants was based, for example, on the following experimental results. In the fixed /i/ context, /a/-on-C effects tended to be smaller and shorter in “consonants requiring more active tongue-dorsum control” (p. 553) than for bilabial /p/ and alveolar /n/. Another result supporting their classification was that in the fixed /a/ context, velar and alveolopalatal consonants allowed lesser vocalic coarticulation than /p/ and /n/. Higher CR value for /k/ obtained in the present study and asserted in Recasens et al. (1997) does not agree with the interpretation of lingual coarticulation in velar consonants presented in Fowler & Brancazio (2000). They compared anticipatory V-on-C coarticulation in bilabial, alveolar and velar consonants, and found that velar consonants patterned with labials, in that they allowed more V-on-C coarticulation than alveolar consonants. These results mostly came from comparing the displacement in the x dimension of a coil placed “as far back on the tongue as the subject could tolerate” (p. 8). These differences between studies are perhaps due to different angles of looking at CR. While Recasens et al. suggested that /k/ is highly resistant because it has a high tongue dorsum position and can impede cross-vocalic coarticulation, Fowler and Brancazio found velars low resistant because their tongue position in English can shift across vowel environments without perceptual damage. The present experiment, due to the fact that the whole tongue contour was analysed, produced results differing from EMA results of Fowler and Brancazio. The tongue position did indeed differ in /k/ across the two vowel environments, but considerably less than in alveolar consonants. Inertia of the tongue dorsum, the active articulator for /k/, has certainly contributed to this closeness in the consonant tongue contour across the two vocalic contexts. A speculation point arising from these discrepancies in interpretations of CR is that there are different angles to CR, and provided there is no confusion in terminology, studies conducted at these different angles can provide useful complementary data.

Other lingual consonants in the present experiment exhibited intermediate (between labials and /k/) degrees of CR. This result is in agreement with the Recasens' classification based on degree of tongue dorsum activation during a sound's production. It should be noted that in Recasens et al.'s experiment, the consonant /s/ displayed a higher CR than other alveolar consonants. A substantial /s/-on-/i/ effect in tongue dorsum lowering was interpreted by Recasens et al. to suggest that manner of articulation may cause an increase in CR value of a phoneme. Some data on /s/ being opposed to other alveolar consonants is presented in Mooshammer et al. (2007). In their work, tongue tip and jaw movements in /aCa/ sequences were studied with EMA, and it was shown that in all alveolar consonants except /s/, a low tongue tip position accompanied a low jaw position; /s/, on the opposite, had a low tongue tip position, but a relatively high jaw position. In our results, /s/ was highly resistant in one subject, while in the other subject /s/ patterned with other alveolar consonants. These findings do not allow us to conclude that manner of articulation in /s/ necessarily causes it to have a higher resistance to lingual coarticulation.

4.2. Vowels. CR of a phoneme across various contexts.

CR values for the two vowels, unlike consonants, were quantified in many pairs of segmental context. Therefore, the results of these calculations give evidence about how much a given sound resists coarticulatory influence of various environments. As shown in Section 3.2, in both subjects consonant pairs including /k/ had the greatest effect on the vowel /a/, and consonant pairs including /l/ had the greatest effect on the vowel /i/. The data on vowel-consonant distances presented in Section 3.1 show that /a/-/k/ and /i/-/l/ distances were very large, compared to most other consonants. So we could suggest at this point that the greater the distance between two adjacent sounds, the more they can influence each other. However, /a/-/t/ and /i/-/s/ distances were also very large, but these consonants paired with other consonants did not contribute as much to the size of effect on the vowel as /k/ and /l/ on /a/ and /i/, respectively. This means that there is another factor contributing to the degree of segments' resistance to lingual coarticulation. As our results suggest, this factor is the distance between the conditioning environments. Analysis of the CR values of the two vowels demonstrated that the vowels resisted most to homorganic consonant pairs. This suggests that if the conditioning sounds are close to each other in lingual position, then the target phoneme has more chances of retaining its lingual position identity across these two contexts. The structure of the formula introduced in this article also highlights the fact that the distance between two neighbouring phonemes is a factor contributing to the degree of resistance of both these phonemes to each other. Gathering more midsagittal tongue contour data on the relation of adjacent phonemes (not necessarily VC sequences) would allow us to obtain more information on mutual resistance of various combinations of phonemes.

A question may arise about the rationale for using a special formula for measuring CR, if there is an apparently more direct measure of coarticulation, i.e., the V-on-C and C-on-V effect size. The answer is that measuring simply the effect size is not sufficient for cross-speaker comparison and generalisations, because the size of effect is reported in millimetres. The CR value, on the opposite, is a ratio. So quantifications based on CR values can be applied to speakers with varying shapes and sizes of the vocal tract, such as children and/or clinical populations.

There is some evidence in our data, though not very strong, suggesting that the vowel /i/ is more resistant to the consonantal influence than /a/. In both subjects, C-on-V effects were larger for /a/ (significant only in S1), and the vowel /i/ had higher

CR values (significant only in S2). Also, the vowel /i/, unlike /a/, was highly resistant not only to pairs of homorganic consonants, but also to pairs of non-homorganic consonants, more so in S1.

4.3. Comparing consonants and vowels

Results presented in Section 3.3 show that the V-on-C effect was nearly five times greater than the C-on-V effect. Besides, unlike the V-on-C effect, the C-on-V effect was sometimes observed at higher significant levels, and in 30% of the cases the C-on-V effect did not occur at all. CR values of vowels were approximately four times greater than CR values of consonants.

A greater vocalic influence on consonants than consonantal influence on vowels is in accordance with Hewlett & Zharkova (under review), where the V-on-C effect for the consonant /t/ was found to be approximately 3 times greater than the C-on-V effect for the vowel /a/. To compare this experiment's results with our previous study more directly, we can look specifically at the segments that were studied in Hewlett & Zharkova (under review): namely, /t/ in the context of /i/ and /a/, and /a/ in the context of /t/ and /k/. In this study, the V-on-/t/ effect was 7.61 mm for S1 and 7.75 mm for S2; the effect of the consonant pair /t/-/k/ on /a/ was 2.42 mm for S1 and 2.47 for S2. The ratio of the V-on-C to the C-on-V effect for each subject is 3.14. This accords very well with Hewlett and Zharkova's results. Slight differences may be explained by the fact that the present study focused on the Standard Scottish English, while Hewlett & Zharkova (under review) analysed data from Southern British English speakers.

It can be argued that the data for the whole tongue contour are not relevant for representing CR characteristics of lingual consonants, which have only a localised constraint on tongue position. However, these data allow for visualising and quantifying a difference in lingual coarticulation between vowels and consonants. The data of this kind can be used in order to approach the question of quantification of lingual consonants' CR based on the constrained tongue region. The data reported in this study do not suggest an easy answer to this question, because ultrasound does not normally provide information on individual flesh points, thus making it impossible to select regions on the tongue curve based on the tongue's physical characteristics (cf. e.g. Shawker et al., 1985, for imaging flesh points using ultrasound). Recent studies of lingual coarticulation using articulatory techniques do not suggest practical ways of calculating degree of resistance to lingual coarticulation based on the data from constrained tongue regions (e.g., Gordon et al., 2007; Iskarous, 2007). Ultrasound data synchronised with EMA data would be useful for quantifying CR of lingual consonants from selected regions of the tongue contour, when such a system becomes available.

Our findings about the difference between V-on-C and C-on-V effect sizes partly confirm the results presented in Keating et al. (1994), where measurements of jaw height were taken, and vowels were shown to exhibit a significant effect on consonants, but the C-on-V effect had only a trend towards significance. The results of this experiment suggest that consonants have a significantly greater susceptibility to segmental lingual coarticulation than vowels. In this experiment, prosodic factors were not used as an independent variable for measuring segmental coarticulation, unlike in Keating et al. (1994). An interesting question for a follow-up study is whether an ultrasound experiment on lingual coarticulation would yield results comparable to Keating et al.'s jaw data – namely, whether in varying prosodic conditions vowels would exhibit more variability of lingual position than consonants.

5. Acknowledgements

The formula for measuring coarticulation resistance used in this study was modified from the formula suggested by Nigel Hewlett for quantifying coarticulation using midsagittal tongue contours. Thanks to Alan Wrench for help with the ultrasound analysis software, to Steve Cowen for technical support, and to the audience at Ultrafest 2007 for comments. This work was supported by an ESRC postdoctoral fellowship, number PTA-026-27-1268.

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